

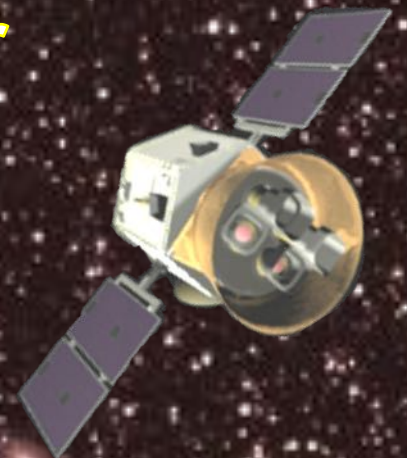
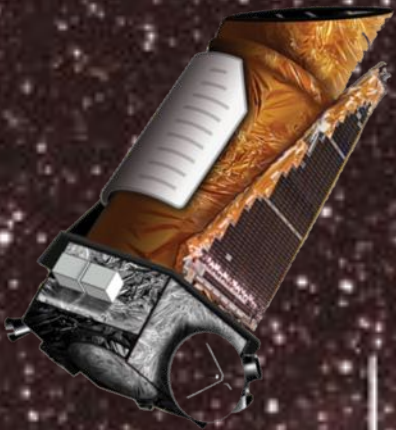
Time Series Analysis in the Search for Other Worlds through Transit Photometry

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NASA Ames Research Center

Monday January 21 2019

Astronomical time Series 2019

**Max Planck Institute for Astronomy
Heidelberg, Germany**





Overview



- **The Science Operations Center Pipeline**
- **Solar Variability**
- **Detection Theory**
- **A Wavelet-based Adaptive Matched Filter**
- **Observations of Stellar Noise on Transit Timescales**
- **Excess Stellar Variability**
- **Summary**

KEPLER

SCIENCE DATA PROCESSING PIPELINE

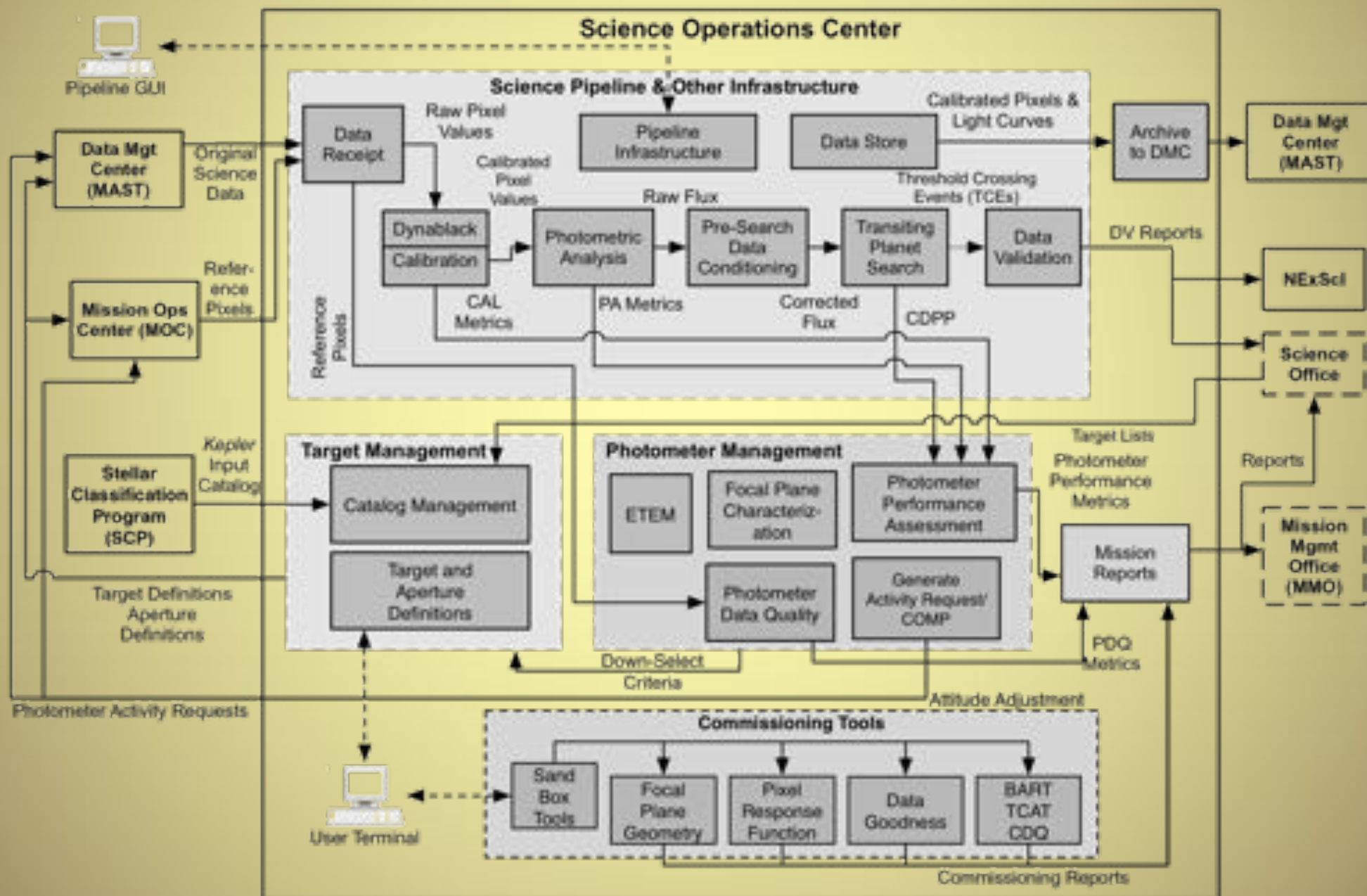




Science Operations Center Architecture

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A Search for Earth-size Planets

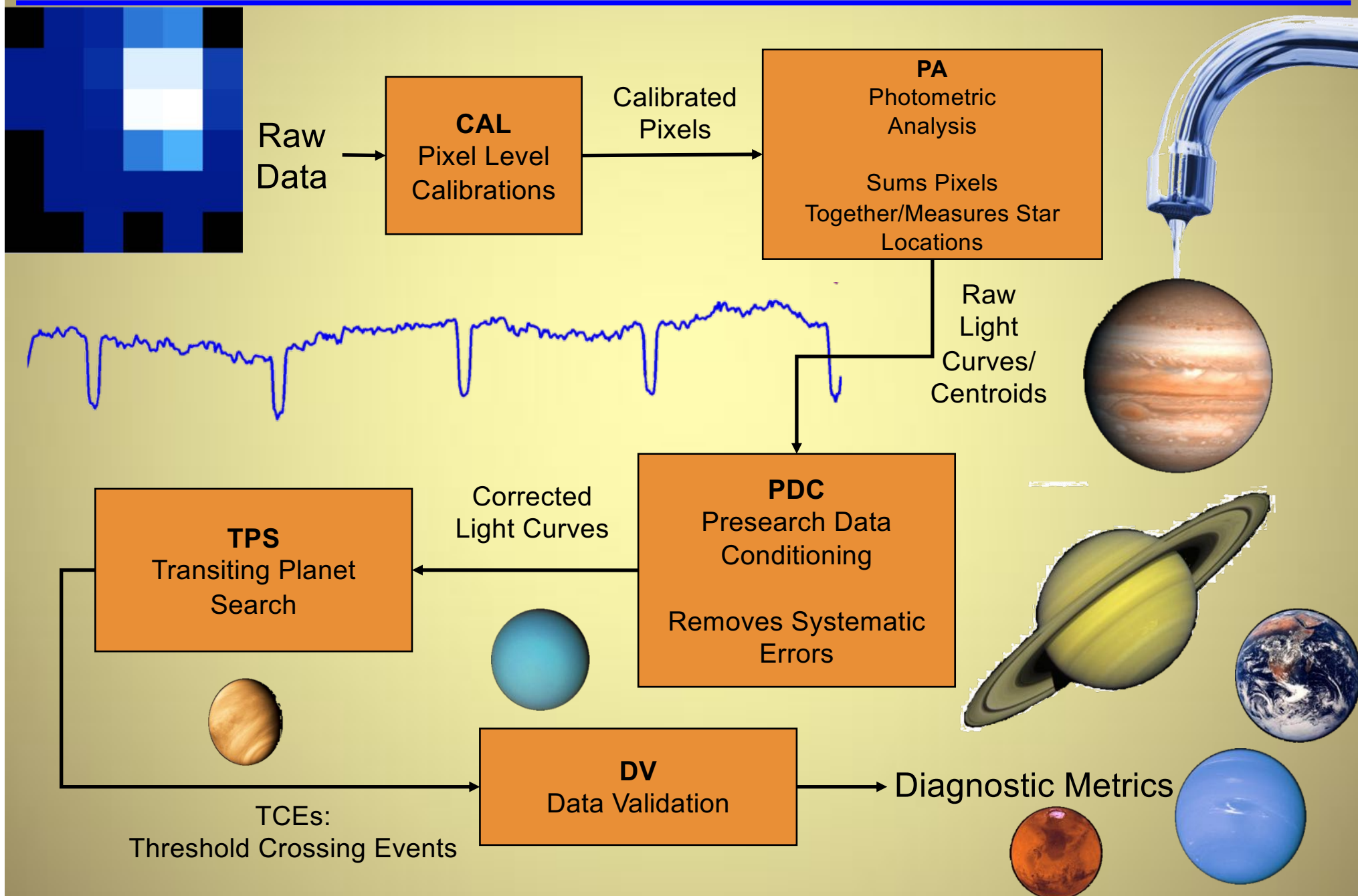




The Kepler Science Pipeline: From Pixels To Planets

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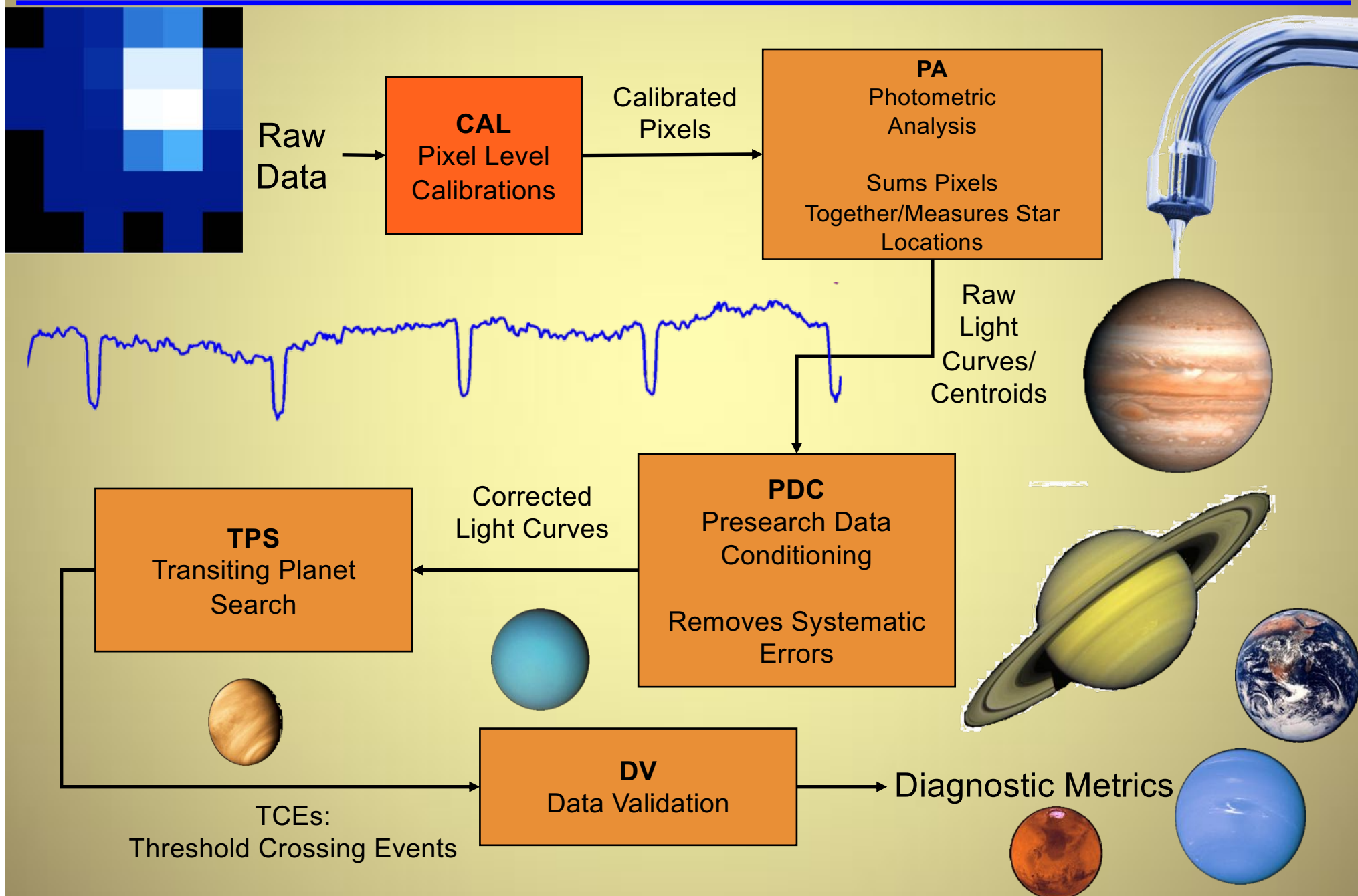




The Kepler Science Pipeline: From Pixels To Planets

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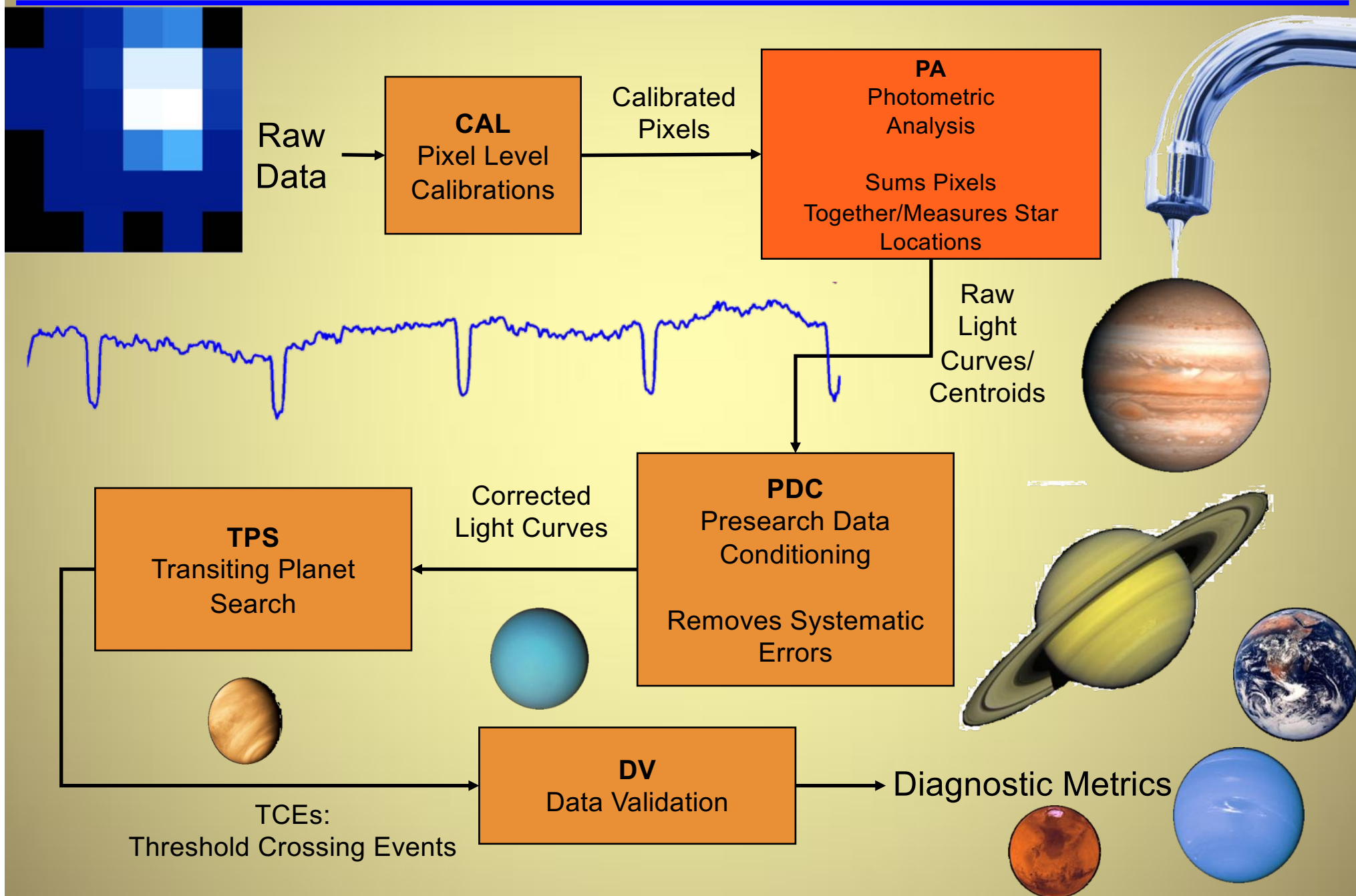




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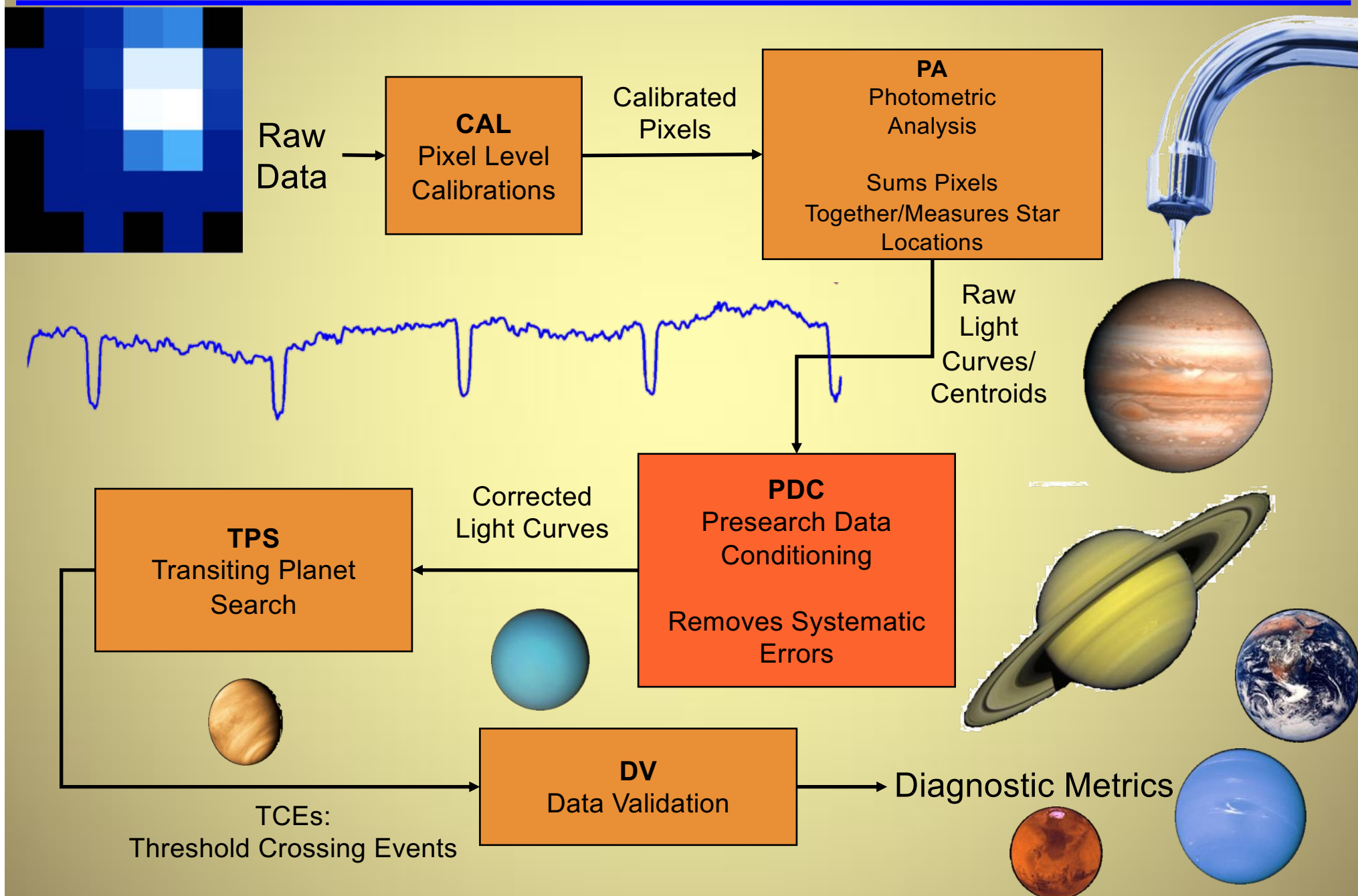


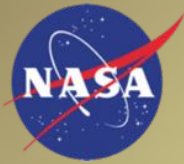


The Kepler Science Pipeline: From Pixels To Planets

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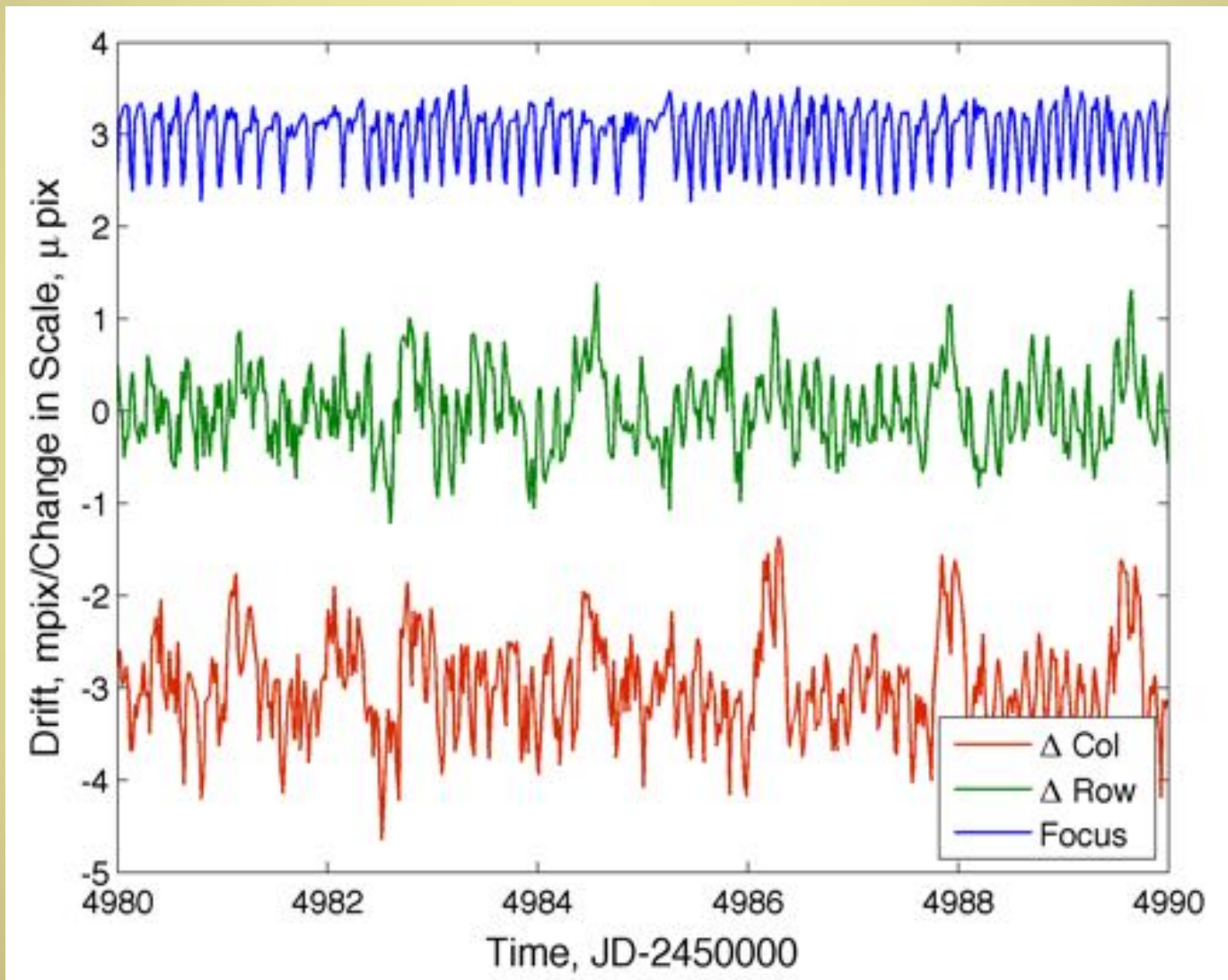
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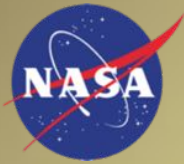


Short Timescale Instrumental Errors

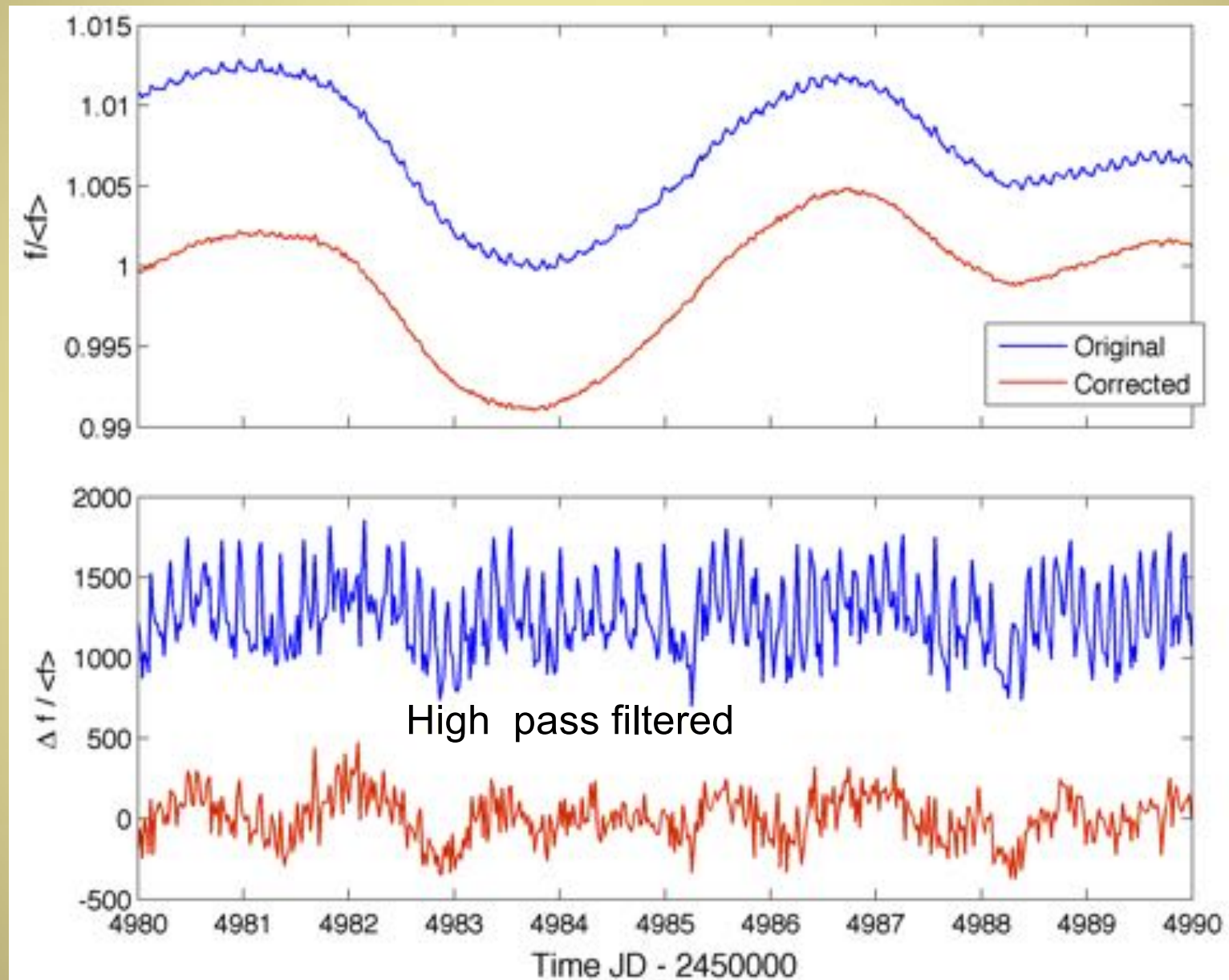
Signature of a heater cycling on the reaction wheels 3/4



Kepler is sensitive to its thermal environment

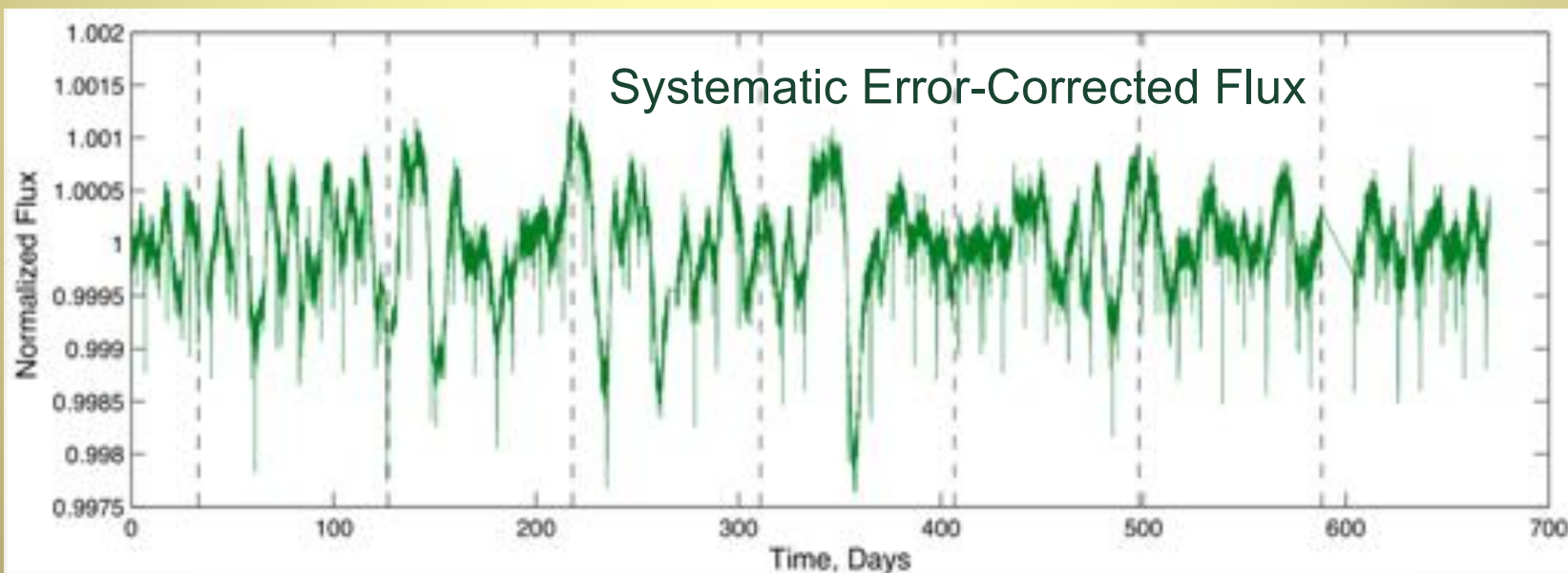
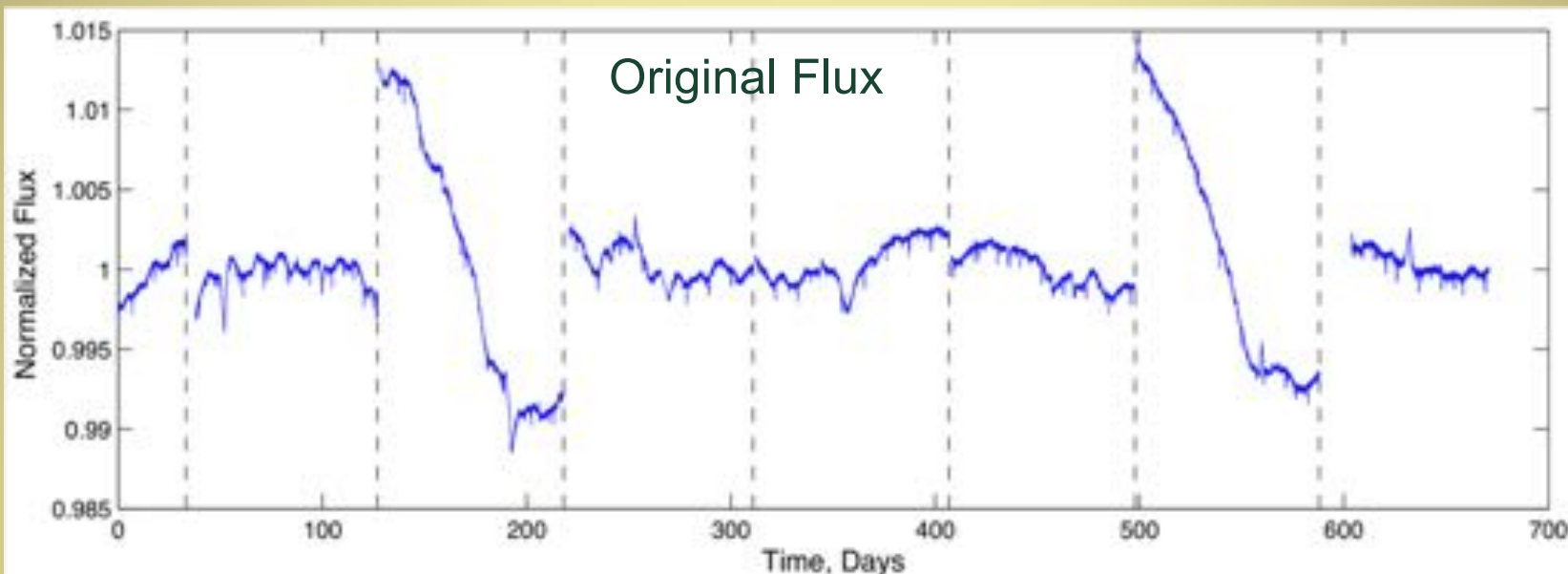


Instrumental Effects in Photometry





Correcting Systematic Errors



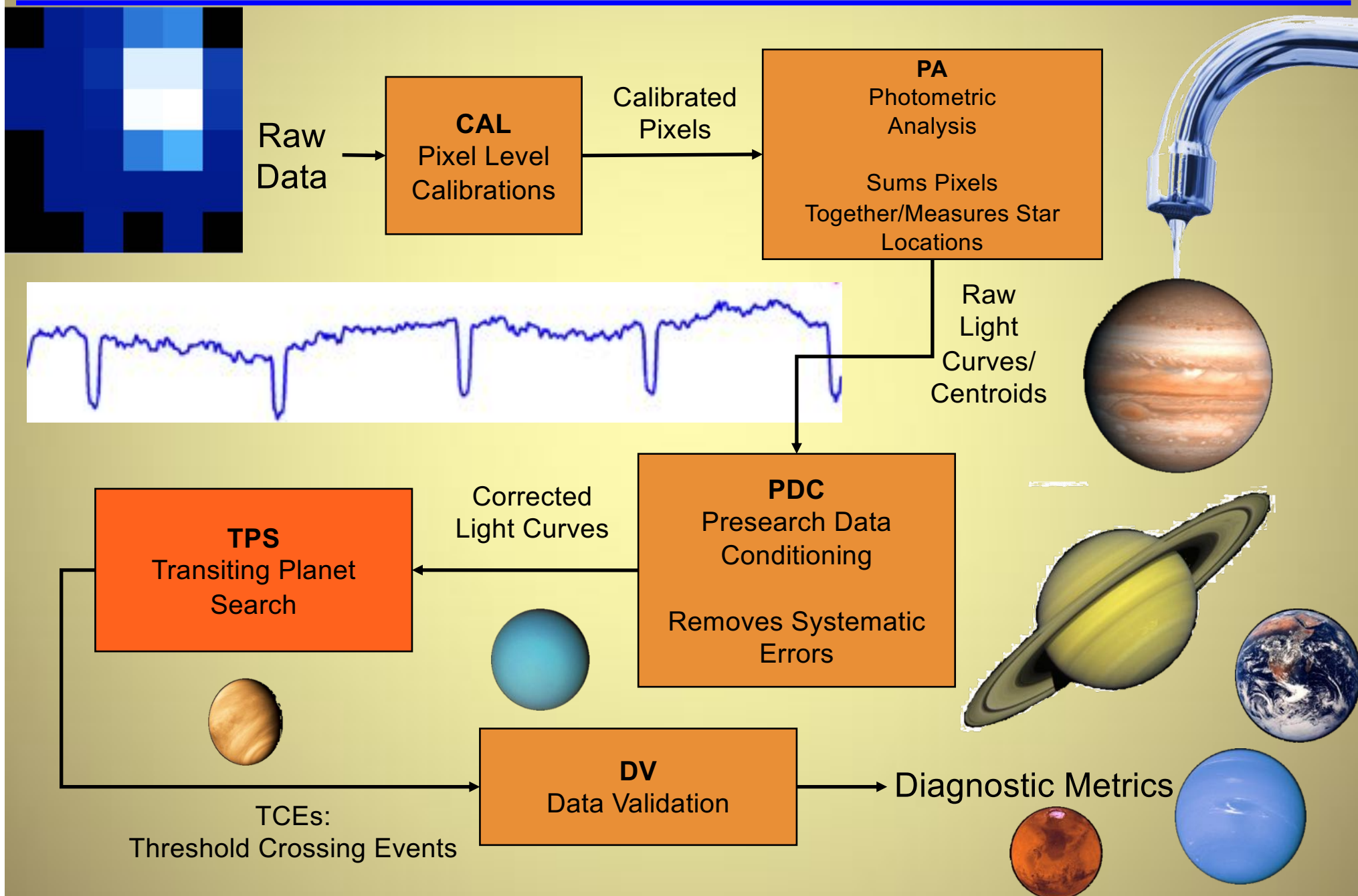
We apply a Maximum A Posteriori approach as per Stumpe et al. 2014



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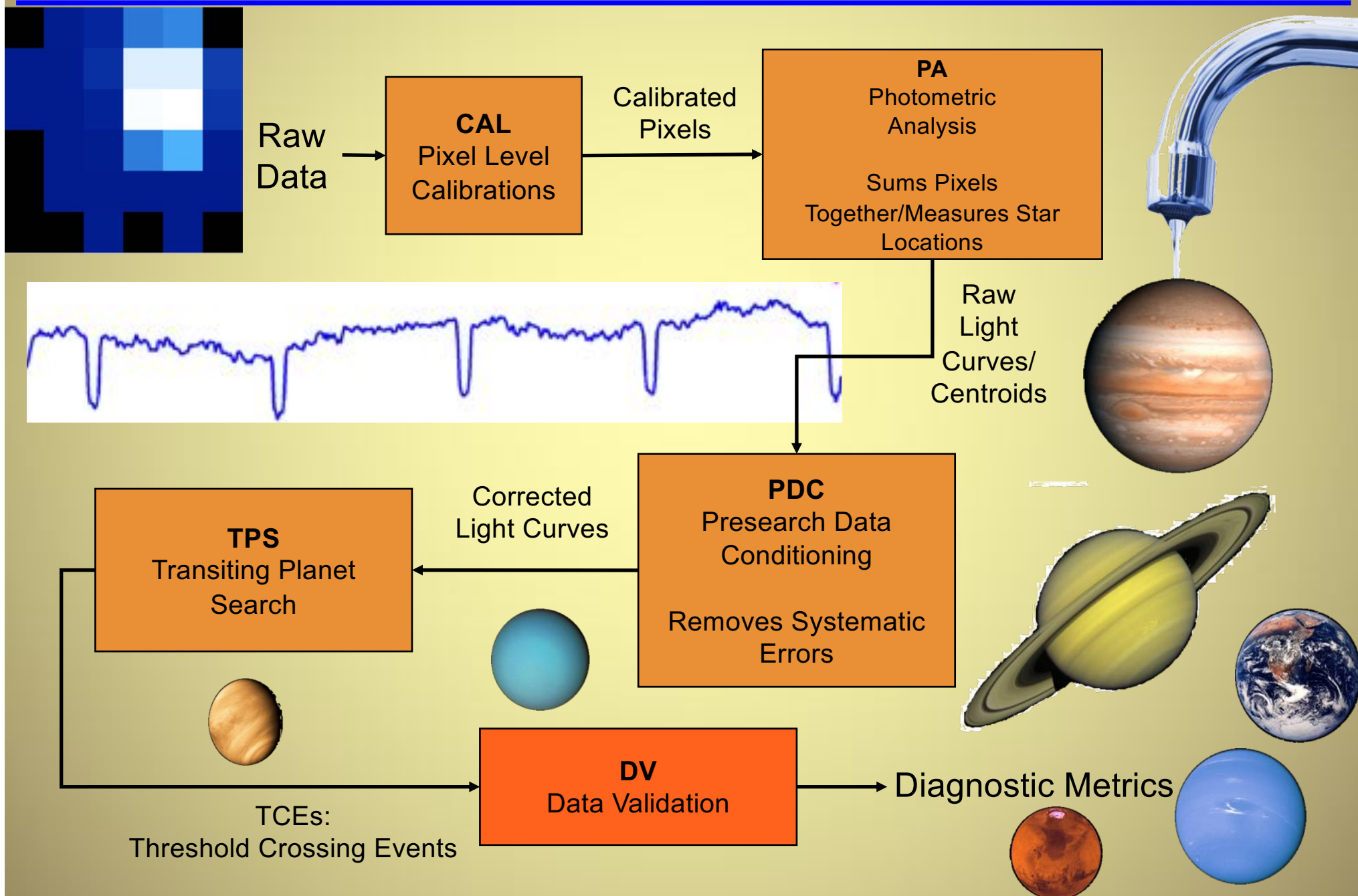
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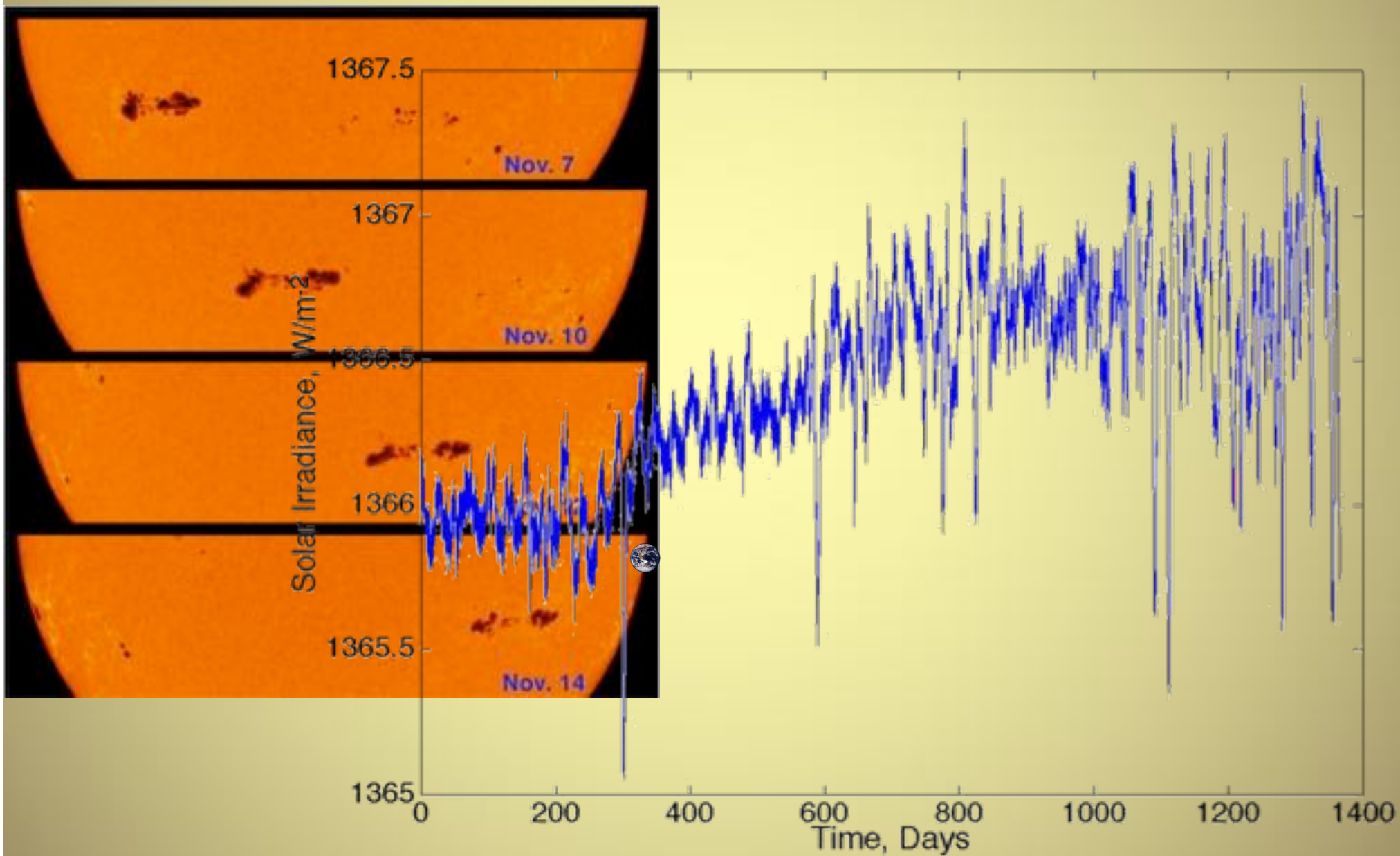




Solar Variability

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Detecting Deterministic Signals

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The problem:

- $H_0: x(n) = w(n)$ or
- $H_1: x(n) = s(n) + w(n)$

$s(n)$ is the signal of interest

$x(n)$ is the time series we observe

$w(n)$ is the observation noise (Gaussian)

The best method for detecting a known signal in additive Gaussian noise is a matched filter

A matched filter measures the correlation between the data and the signal, normalized by the rms variation of the observation noise



Detection Statistics

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Define

$$T = \frac{x^T s}{\sigma_w \sqrt{s^T s}}$$

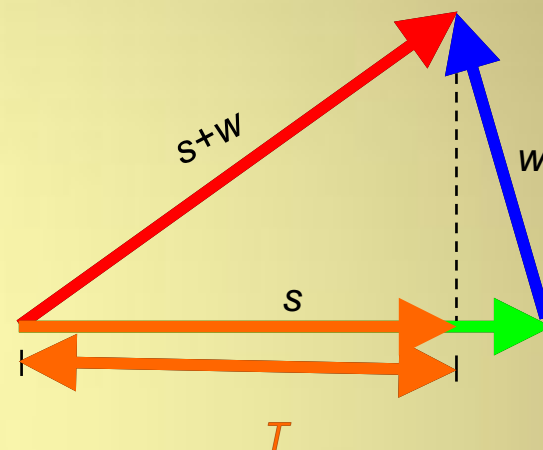
Under H0:

$$\langle T \rangle = 0, \quad \sigma_T^2 = 1$$

Under H1:

$$\langle T \rangle = \frac{1}{\sigma_w} \sqrt{s^T s}, \quad \sigma_T^2 = 1$$

If $T < \gamma$, then choose H0, if $T > \gamma$, then choose H1



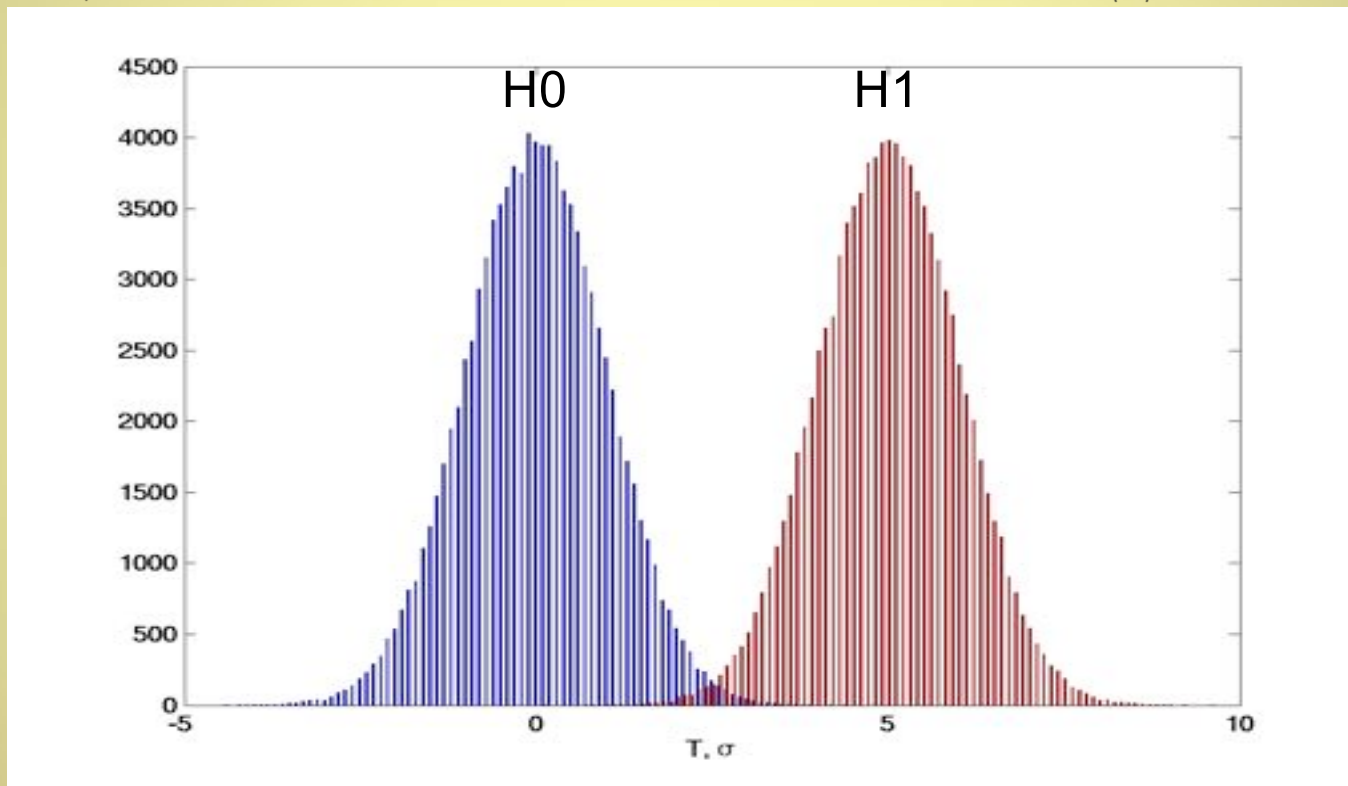


Receiver Operating Curves

T is a Gaussian random variable

$$P_F = \frac{1}{\sqrt{2\pi}} \int_{\gamma}^{\infty} \exp\left(-\frac{1}{2} y^2\right) dy$$

$$P_D = \frac{1}{\sqrt{2\pi}} \int_{\gamma - \langle T \rangle}^{\infty} \exp\left(-\frac{1}{2} y^2\right) dy$$



How do we choose the threshold, γ ?

If amplitude of s not known, we generally set γ to control P_F .
(Neyman-Pearson Criterion)



Detection Statistics For Colored Noise

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w is (colored) Gaussian noise with autocorrelation matrix R

x is the data

s is the signal of interest

Decide s is present if

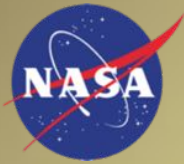
$$T = \frac{x^T R^{-1} s}{\sqrt{s^T R^{-1} s}} = \frac{(Hx)^T (Hs)}{\sqrt{(Hs)^T (Hs)}} = \frac{\tilde{x}^T \tilde{s}}{\sqrt{\tilde{s}^T \tilde{s}}} > \gamma$$

How do we determine R ?

Looks like a simple matched filter!

If the noise is stationary, we can work in the frequency domain:

$$T = \int \frac{X(f)S^*(f)}{P(f)} df \bigg/ \sqrt{\int \frac{S(f)S^*(f)}{P(f)} df}$$



PSDs for Solar-Like Variability



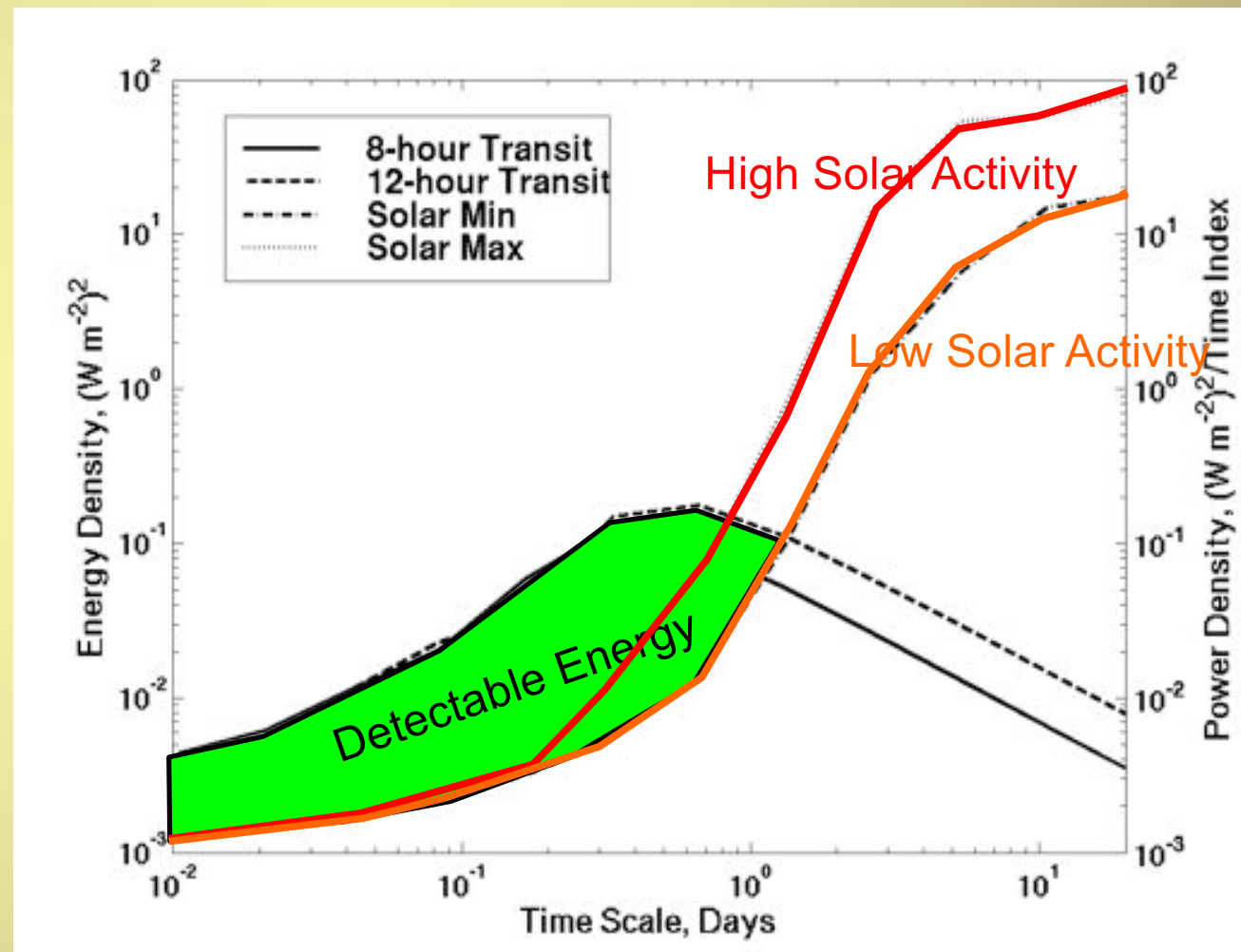
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Is stellar variability stationary?

No!

We must work in a joint time-frequency domain

Wavelets are a natural choice





A Wavelet-Based Approach

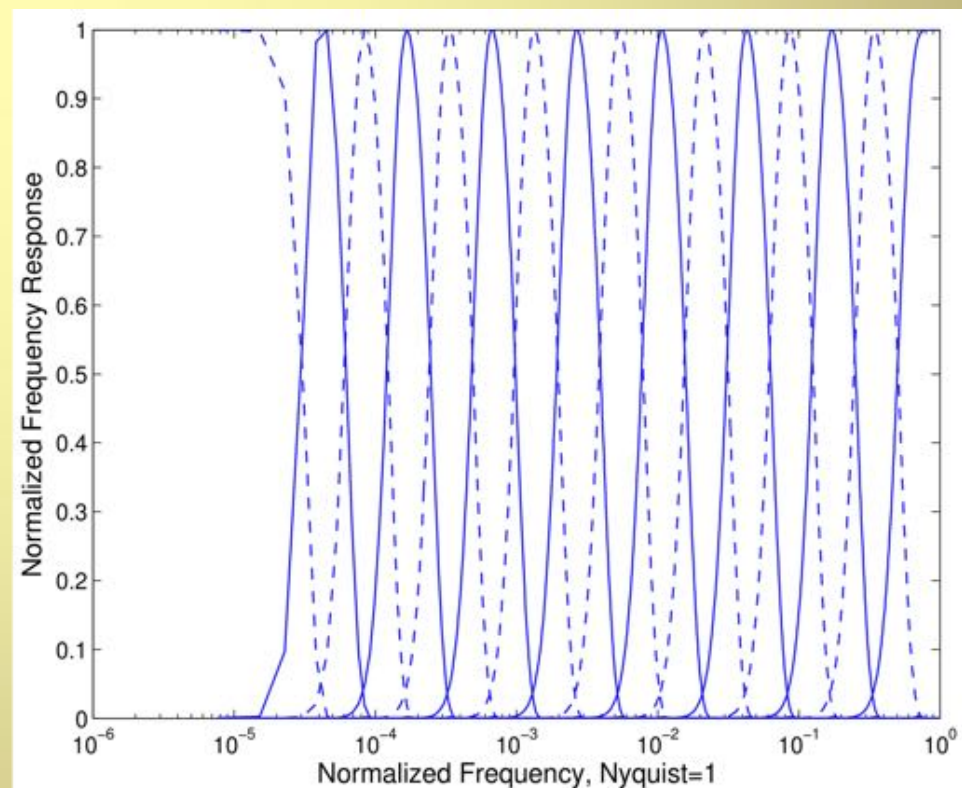
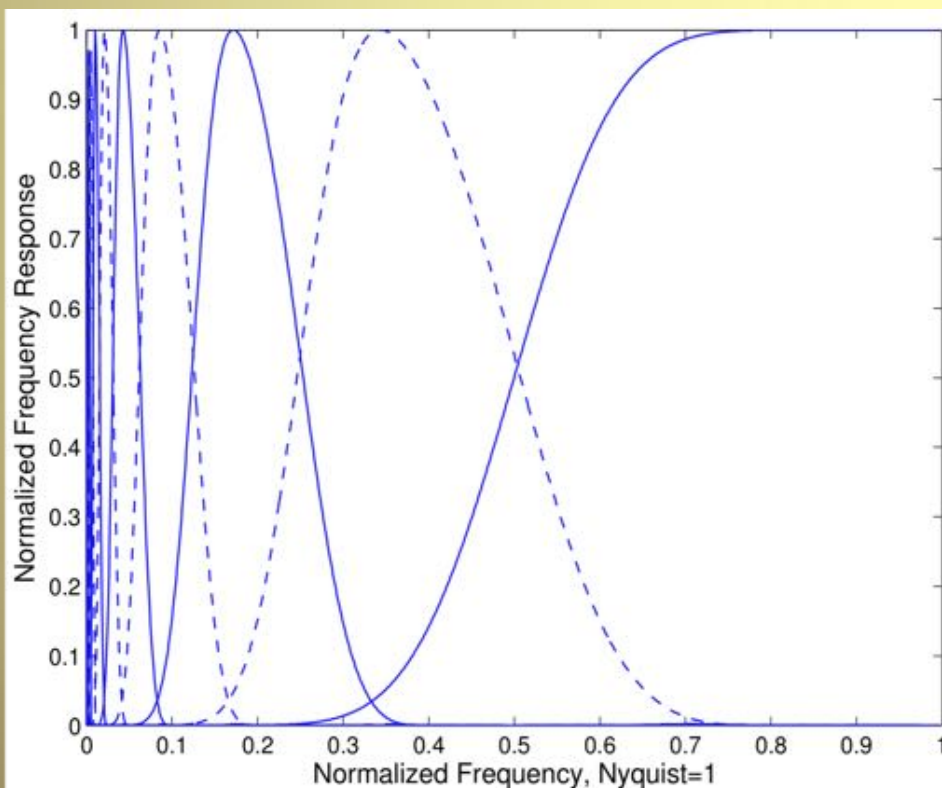
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Filter-Bank Implementation of an Overcomplete Wavelet Transform

The time series $x(n)$ is partitioned (filtered) into complementary channels

$$\begin{aligned} W_x(i,n) &= \{h_1(n) * x(n), h_2(n) * x(n), \dots, h_M(n) * x(n)\} \\ &= \{x_1(n), x_2(n), \dots, x_m(n)\} \end{aligned}$$

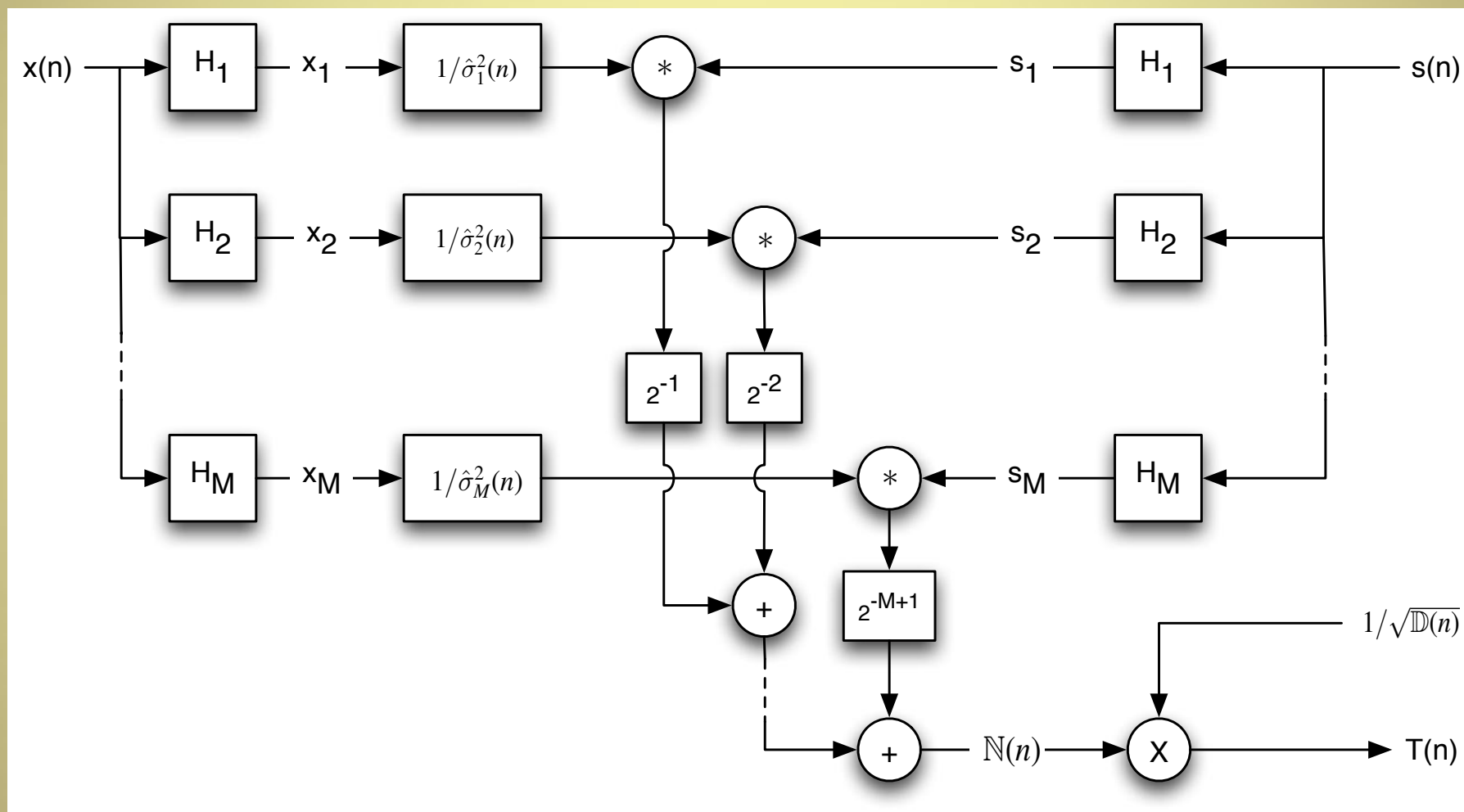




Signal Flow Diagram

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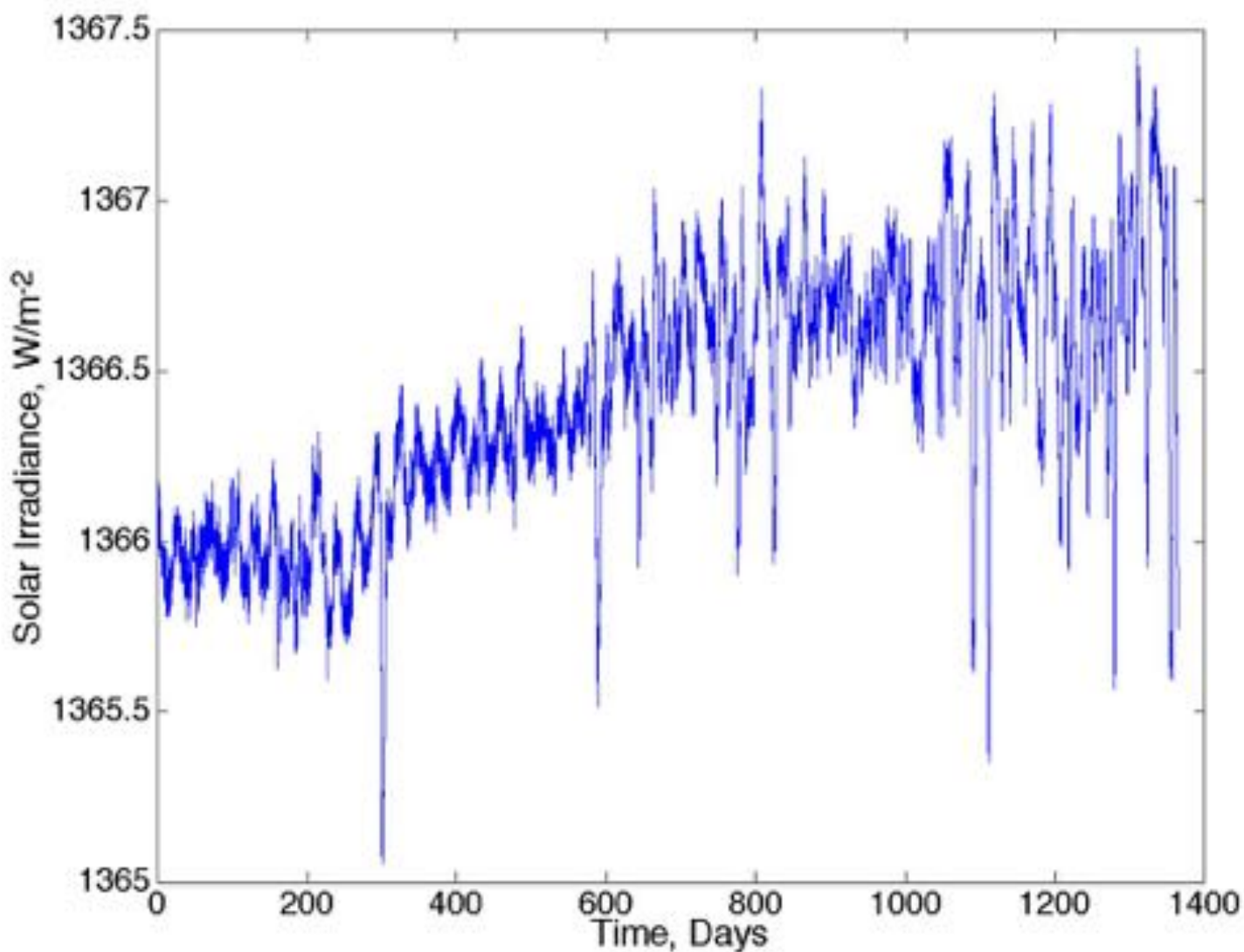




Kepler-like Noise + Transits

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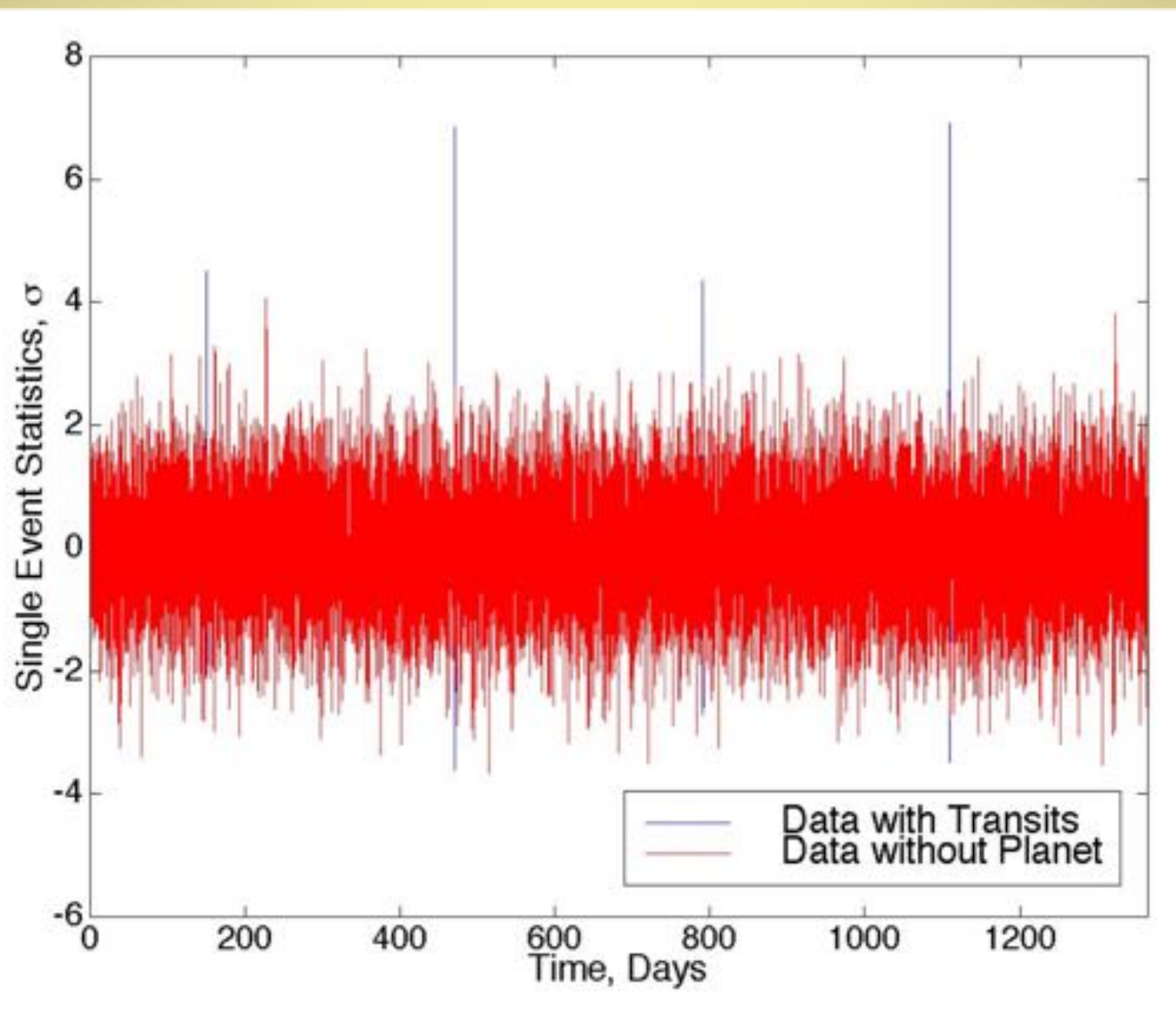




Single Transit Statistics

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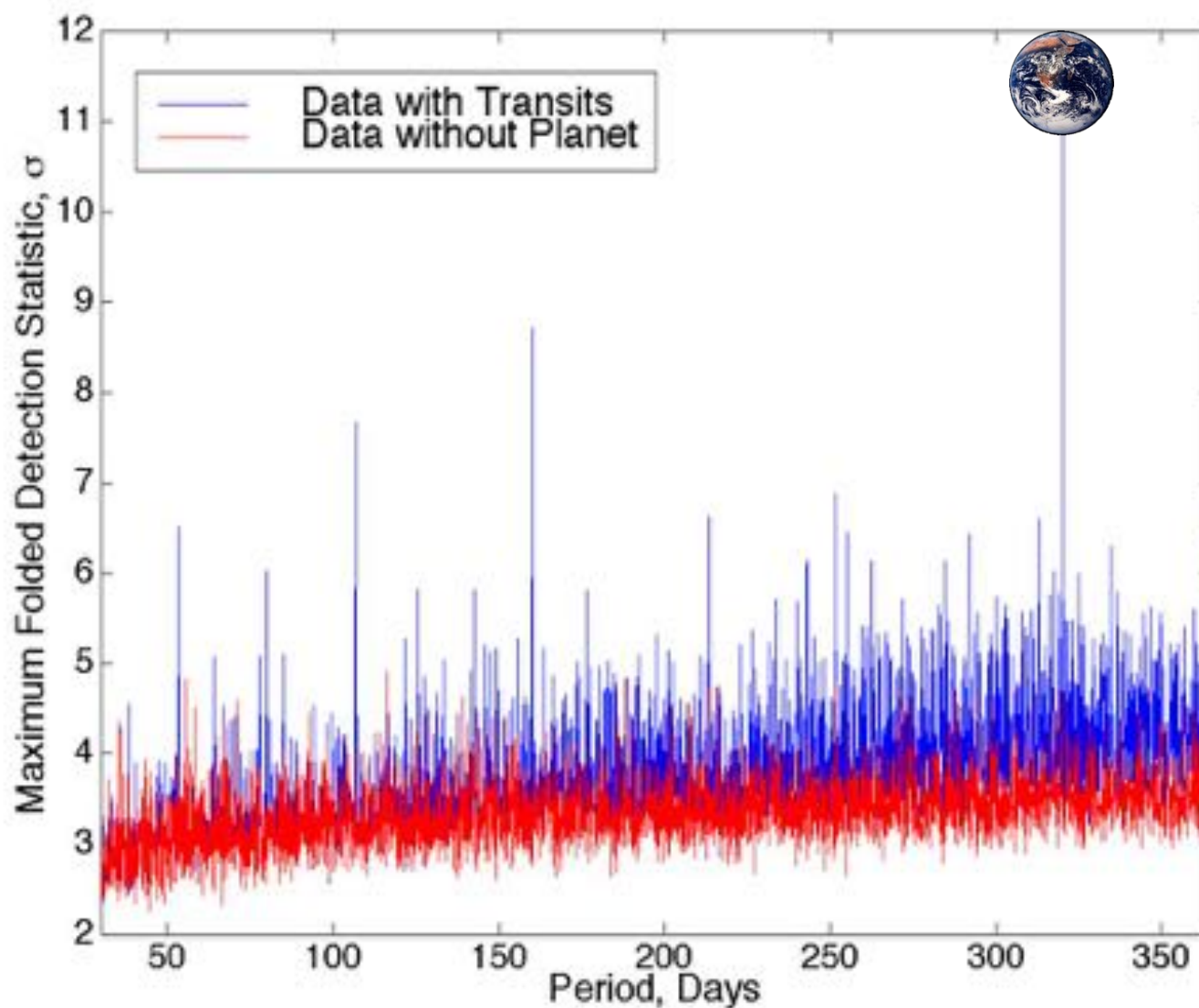




Folded Transit Statistics

Kepler

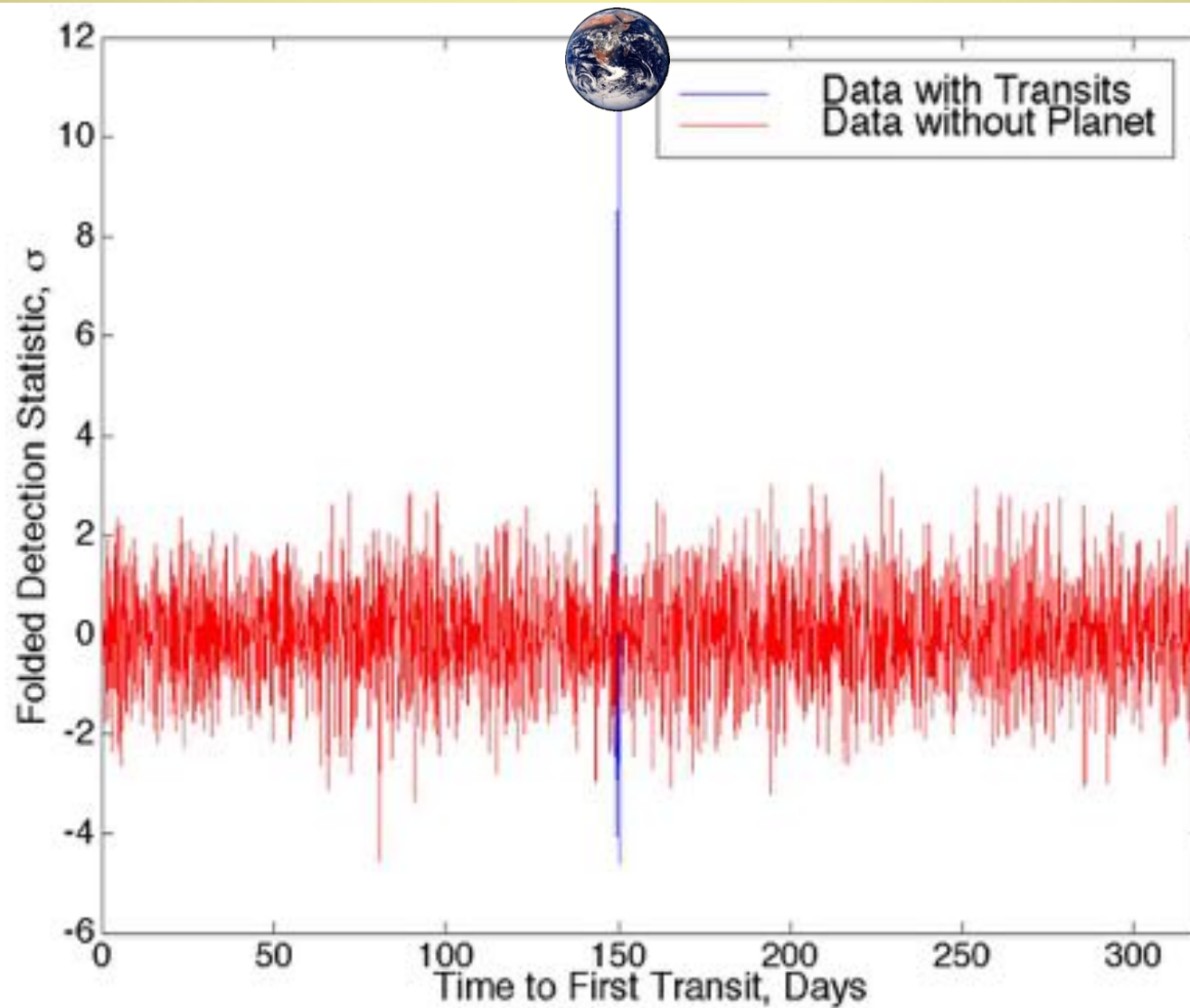
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Folded Statistics at Best-Matched Period

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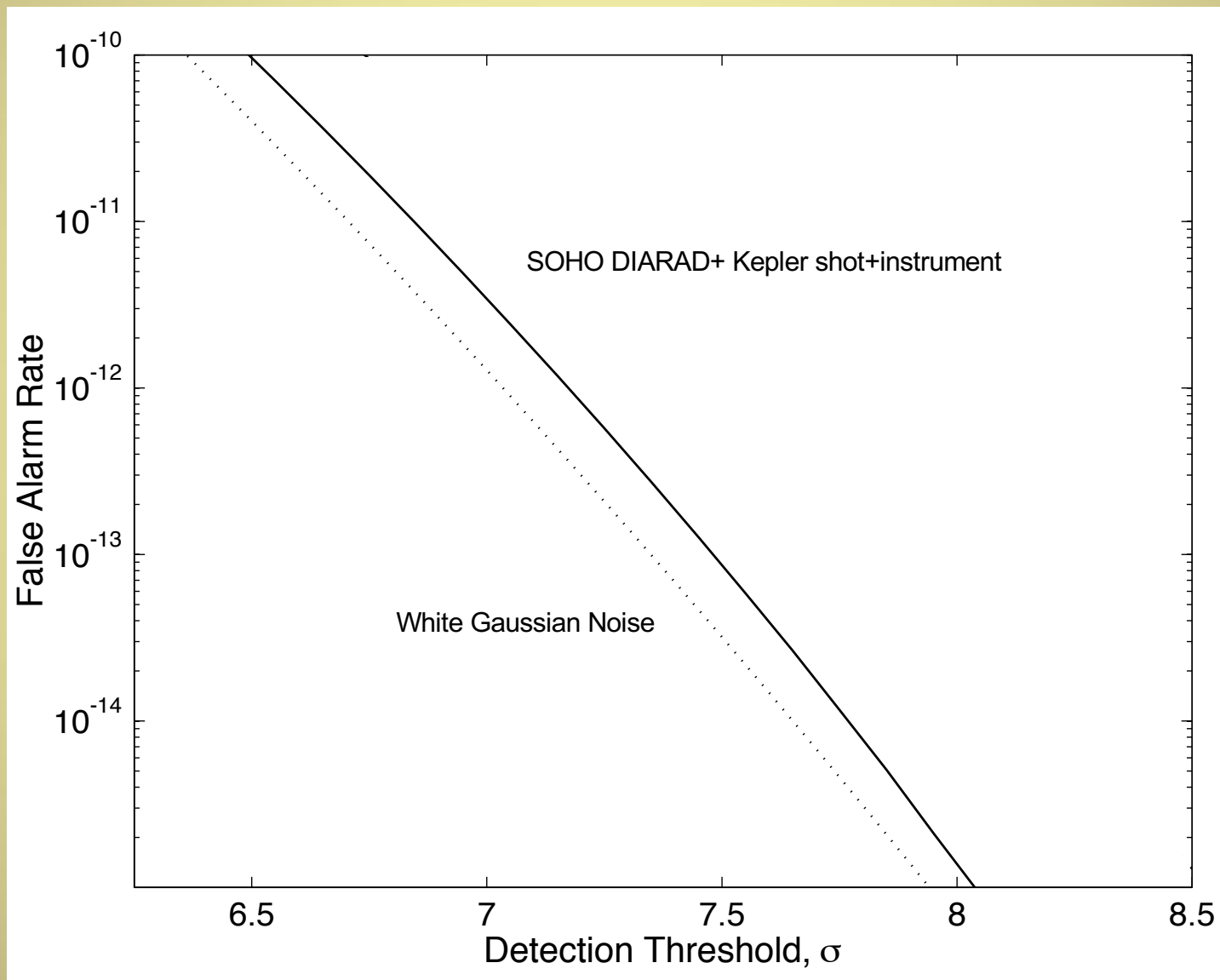




Setting the Threshold

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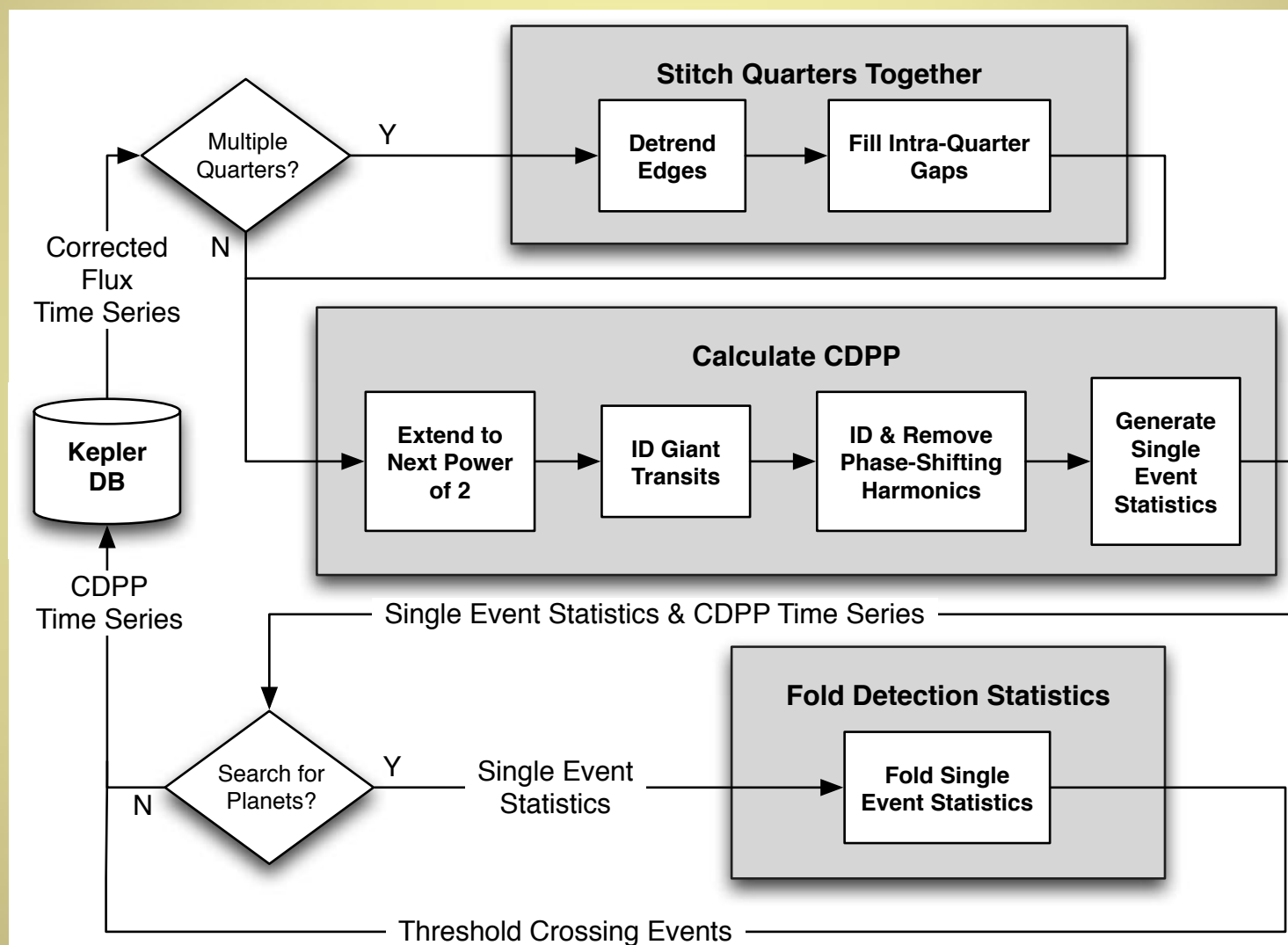




Transiting Planet Search Architecture



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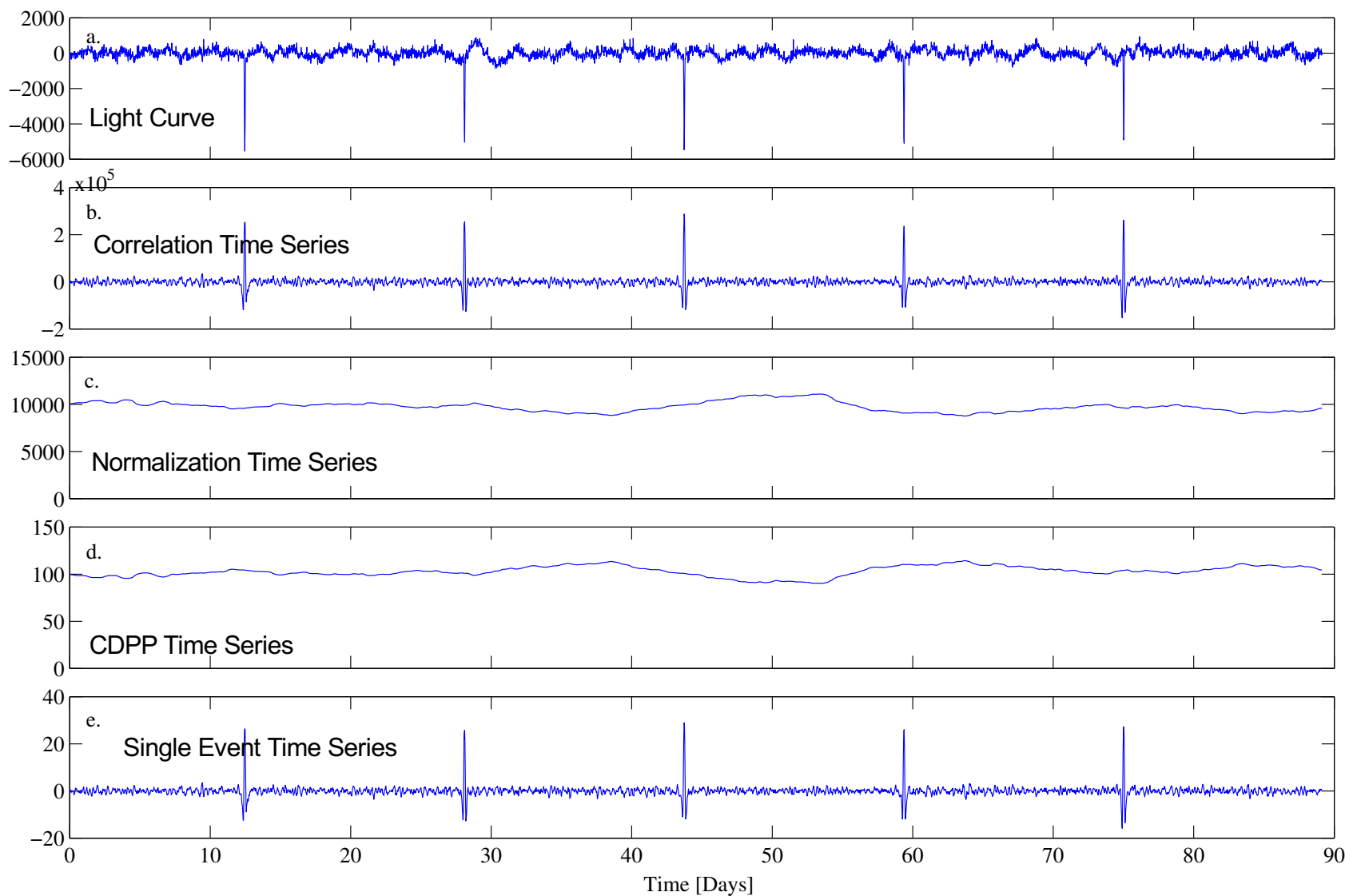




A Kepler Example: Calculating CDP

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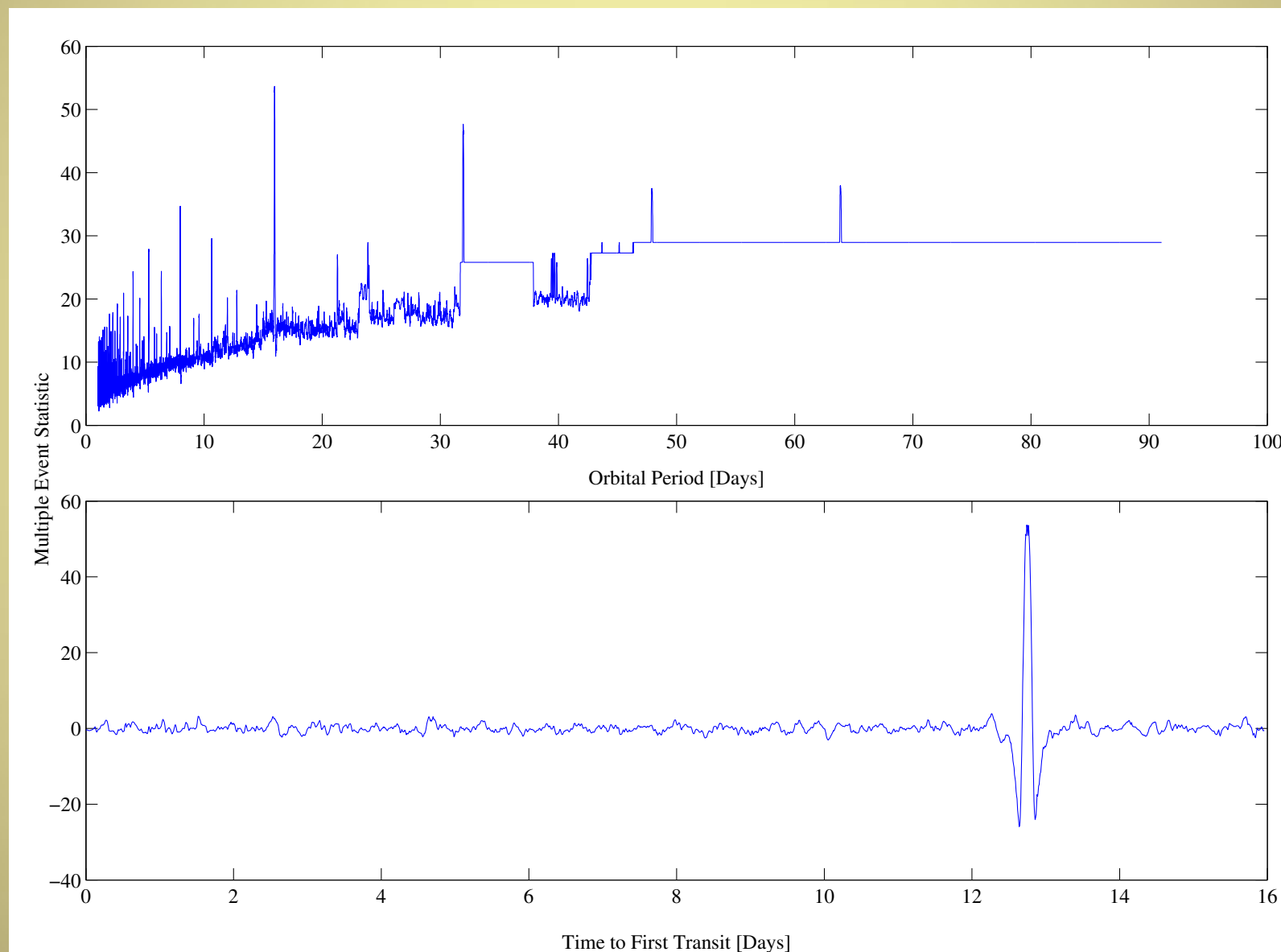




A Kepler Example: Calculating CDP

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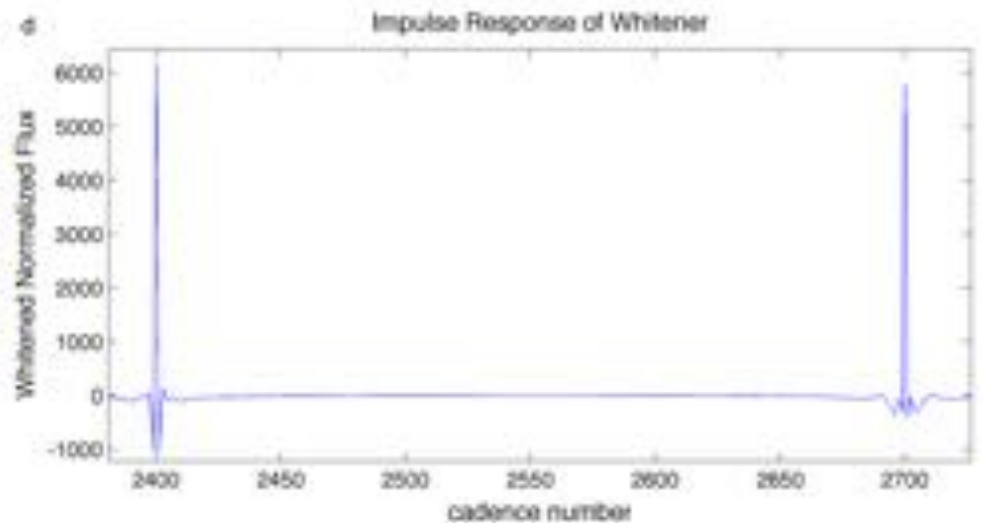
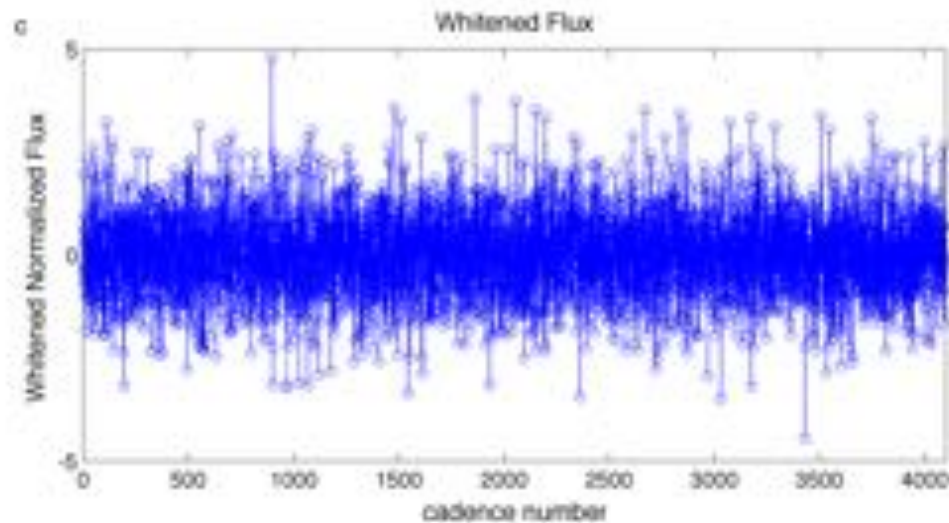
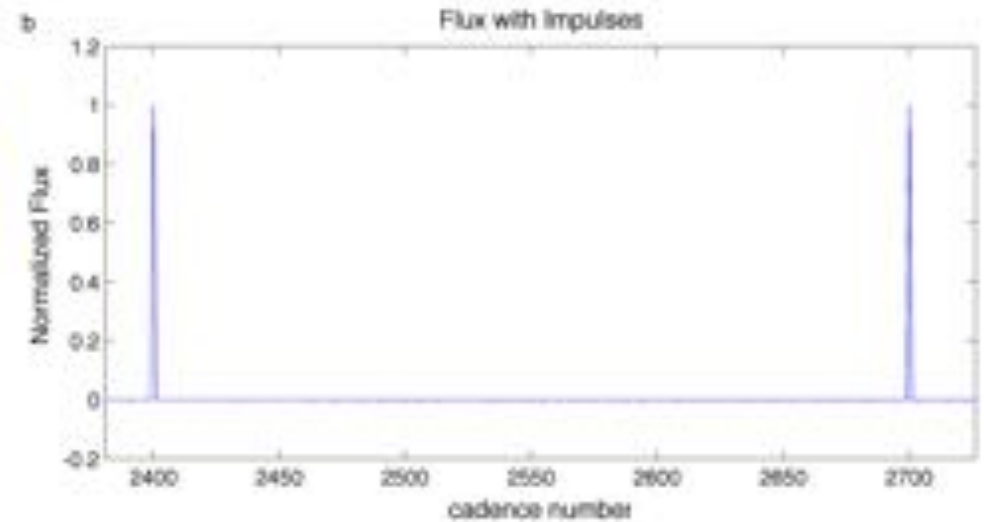
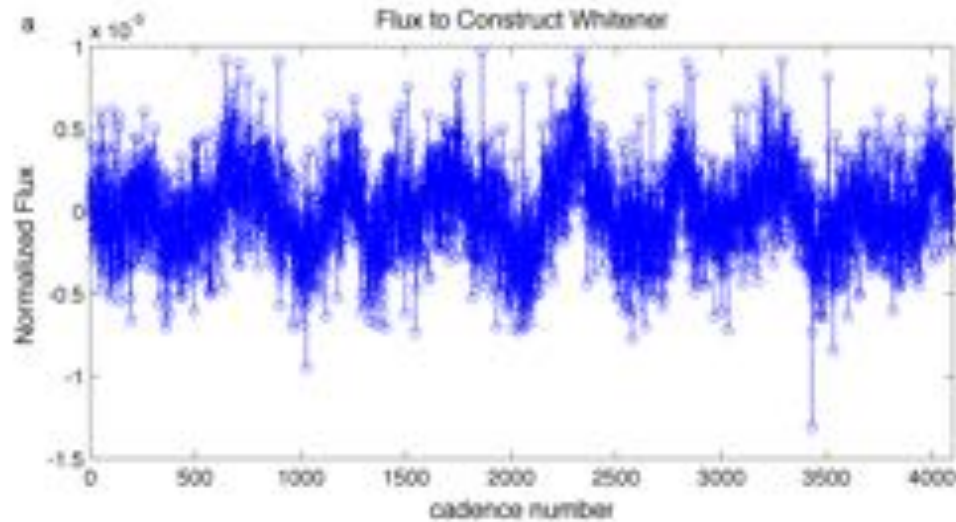




A Kepler Example: Adaptive Whitening

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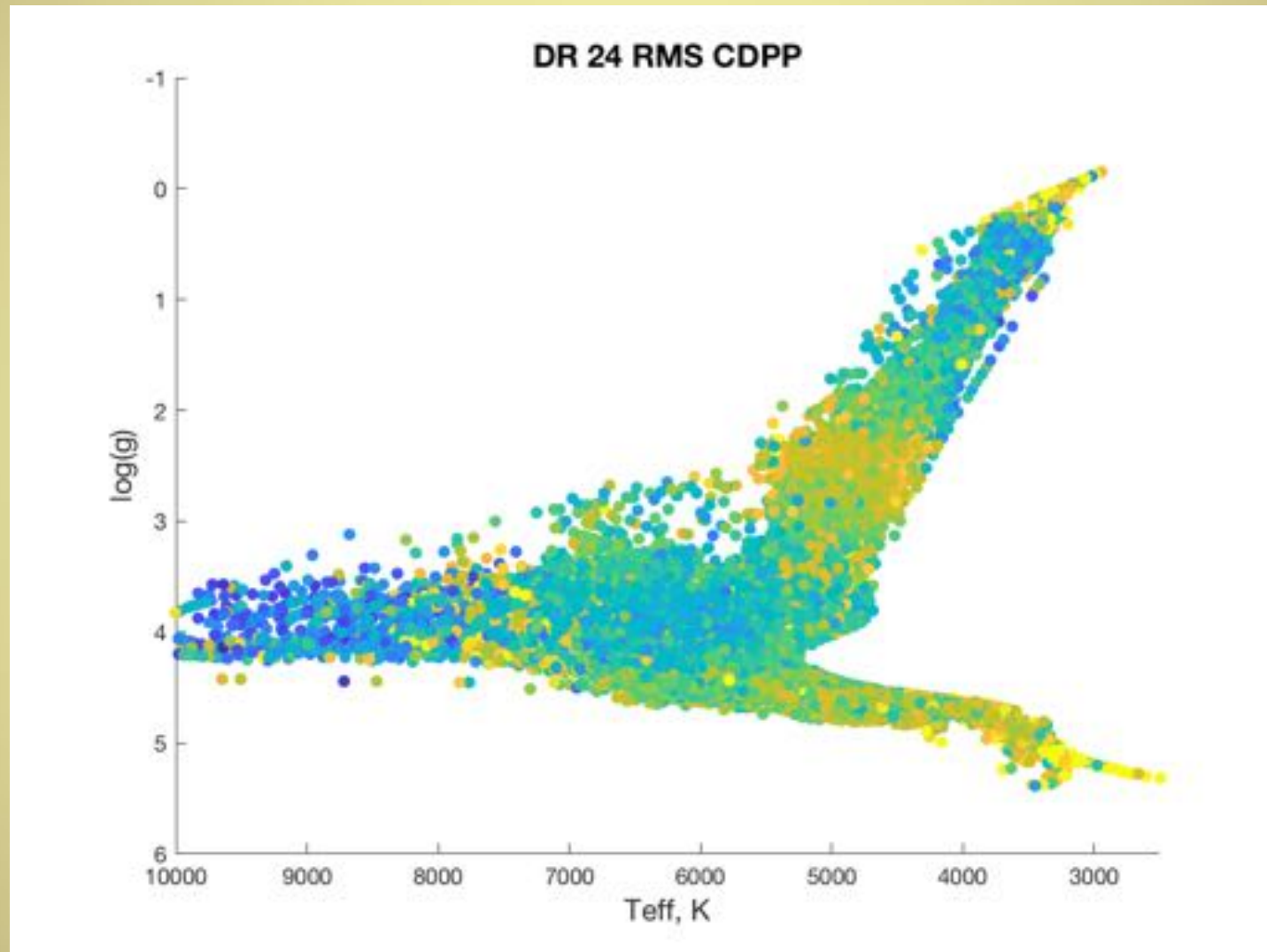




Photometric Precision



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G dwarfs appear to be quiet, and M dwarfs appear to be much noisier



Excess Stellar Variability



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Original Noise Budget

($K_p=12$):

14 ppm Shot Noise

10 ppm Instrument Noise

10 ppm Stellar Variability

=> 20 ppm Total Noise

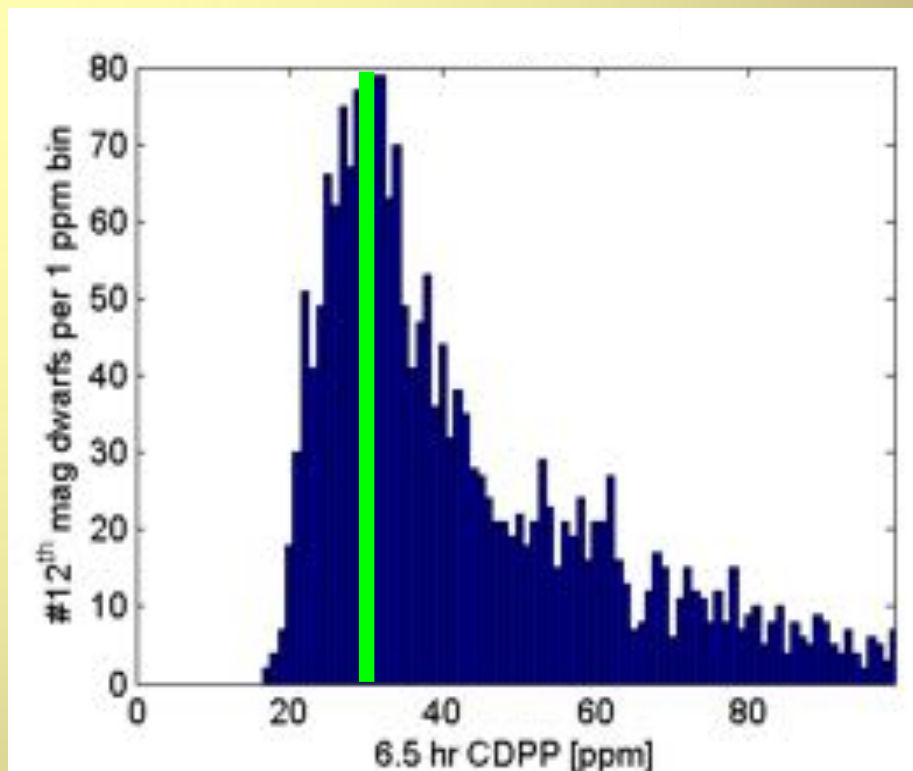
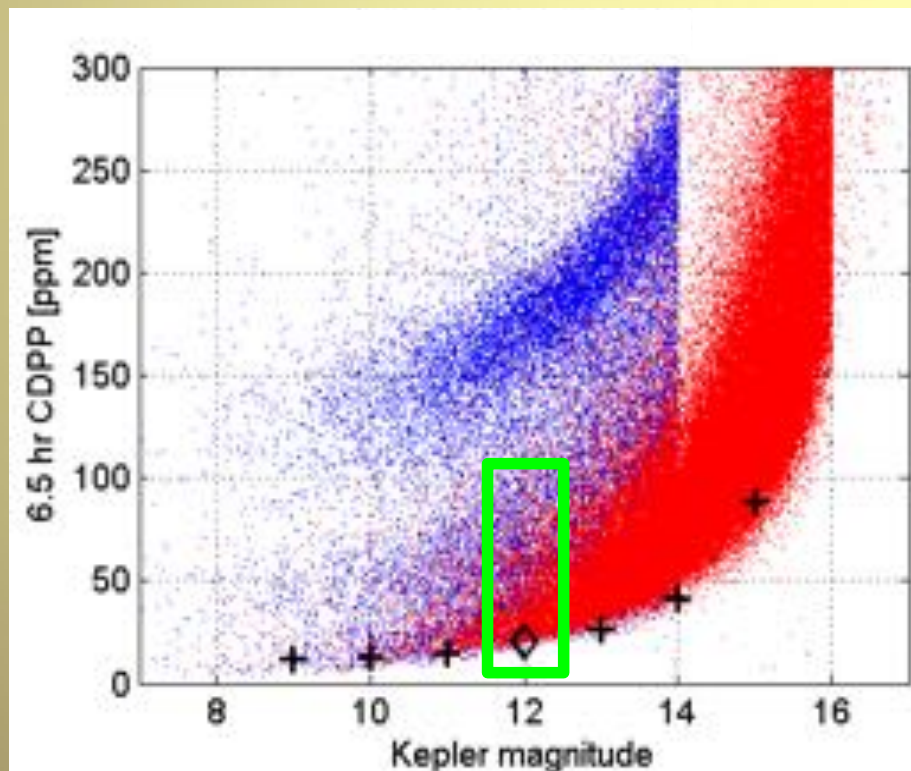
Reality ($11.5 \leq K_p \leq 12.5$)

17 ppm Shot Noise

13 ppm Instrument Noise

20 ppm Stellar Variability

=> ~29 ppm Total Noise





Summary



- Stellar variability presents a fundamental limit on the detectability of transiting Earth-like planets
- Adaptive matched filters can provide near-optimal detection of Earth-size transits and characterize the observation noise
- Larger than expected stellar variability can be compensated for by increasing the duration of the campaign
- Controlling instrumental noise and systematics is also very important as shot noise, instrument noise and stellar variability should be comparable in a well designed mission